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New method for precise determination of top quark mass at LHC

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論 文 内 容 要 旨

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論 文 要 旨

The top quark was discovered in the Tevatron experiments at Fermilab in 1995. It has the largest mass and, as a consequence, the strongest coupling to the Higgs boson among the elementary particles in the Standard Model (SM) of particle physics. This makes the top quark distinct from other quarks and gives it a prominent role in various physics. In electroweak precision fits, the top quark mass is a critical input among the global fit parameters owing to its large contributions to radiative corrections. In addition, assuming that the SM can be extrapolated up to the Planck scale without new physics, the precise value of the top quark mass, together with the Higgs boson mass, settles whether the SM vacuum is stable or not. Furthermore, in models beyond the SM, predictions often depend strongly on the value of the top quark mass. For these reasons, precise measurements of the top quark mass is demanded for tests of the SM and models of new physics.

The top quark mass has been measured by the CDF and D0 collaborations at the Tevatron and the ATLAS and CMS collaborations at the LHC.　A recent combined result of measurements at the Tevatron yields the top quark mass to be 173.34±0.37(stat)±0.52(syst) GeV, which achieves a high precision of 0.37 %. However, there is a problem that the definition of the measured top quark mass is ambiguous theoretically. In the above measurements, the top quark mass is basically obtained from measuring kinematic

distributions of the top-quark final state and comparing the distributions with theoretical predictions simulated by Monte-Carlo (MC) event generators. In the MC generators, phenomenological models are used to simulate hadronization processes since the processes are non-perturbative and cannot be derived from first principles within the framework of perturbative theory. Therefore, the measured mass using jet momenta and fitting to the MC is hadronization-model dependent. It should be distinguished from well-defined top quark masses in perturbative theory, such as the mass in the modified minimal subtraction scheme (which we refer to as MSbar mass hereafter) and the pole mass. Strictly speaking, the measured mass cannot to be used as an input parameter to calculations in perturbative theory, in spite of its high precision.

The pole mass of the top quark, defined as the pole position of the top quark propagator order-by-order in perturbative QCD, also involves a difficulty. Reflecting the fact that a free quark is not observable, the perturbative convergence of the quark pole mass is limited to the order of the QCD scale. To avoid this difficulty, use of the MSbar mass, which improves convergence of perturbative expansions drastically, is favored for various theoretical calculations. Therefore, a precise determination of the MSbar mass is desirable. The values of the MSbar and pole masses of the top quark have been extracted from measurements of top-quark pair production cross section at the Tevatron and LHC. The results of measurements of the MSbar and pole masses read 160.0+5.1/-4.5 GeV by the D0 experiment and 172.9+2.5/-2.6 GeV by the ATLAS experiment, respectively. In addition, recently a new method using the normalized differential cross section of events with top-quark pair plus one jet has been proposed and applied to a measurement of the top quark pole mass. The result yields the pole mass to be 173.7+2.3/-2.1 GeV, which is the most precise measurement of the top quark pole mass currently available. These errors are still large compared to the conventional measurements mentioned above and not favorable for input to theoretical calculations.

In the light of the current status of the top quark mass measurements mentioned above, we intend to realize a precise determination of the top quark MSbar mass at the LHC. In order to achieve this goal, we propose a new method for the top quark mass measurement. This method has characteristics of using only lepton distributions and primarily being independent of the top quark velocity distribution. Owing to the characteristics, it does not depend on hadronization processes and parton distribution functions (PDFs) in principle. Thus, with this method, we can determine the top quark mass based on perturbative QCD and obtain the MSbar mass of the top quark.

Our new method is based on the ``weight function method'' which we proposed aiming at precision measurements of various physical parameters at hadron colliders. The method uses a characteristic weight function. The weight function is a function of the energy of lepton (where a lepton indicates an electron or a muon) and a parameter m which is supposed to be measured. Typically m is the mass of the parent particle. The function can be calculated theoretically with knowledge of the decay process of the parent particle. Assuming that the parent particle is scalar or unpolarized (with respect to its boost direction), a weighted integral $I(m)$ with the following property can be constructed: with $I(m)$ defined by the integral of the normalized lepton energy distribution in the laboratory frame weighted by the weight function,

$$I(m=m^{\mathrm{true}}) = 0\,,$$

is hold, where m^{true} is the true value of m. This property holds irrespective of velocity distribution of the parent particle, though the velocity distribution affects lepton distribution. Therefore, using the characteristic weight function, we can extract the true value of m as the zero of $I(m)$ independently of the velocity distribution of the parent particle. The required observable is only lepton energy distribution.

We study an application of the weight function method to the top quark mass measurement at the LHC. Under real experimental circumstances, we have to take account of deviation from the above ideal limit. The deviation is caused by experimental effects such as detector acceptance, event selection cuts and background contributions. There are theoretical contributions to the deviation as well, such as the effect of the top quark off-shellness. Higher-order corrections in perturbative QCD should also be included. Since the experimental effects could be fatal at the LHC, where huge background events inevitably demand application of strict cuts, we investigate experimental viability of this method in the first place. In this thesis, we present a study of a simulation analysis of the top mass measurement at the LHC with our new method, incorporating the above experimental effects. The analysis is performed at LO, and the theoretical aspects such as higher-order corrections and the effect of the top quark off-shellness are not considered. In this analysis, we study top quarks in top-quark pair production and their lepton+jets decay channel.

The main results of the MC simulation analysis at LO presented in this thesis are as follows:

- We confirmed that the weight function method works well within MC statistical errors using only signal events at the parton level.
- Among experimental effects, we found that the most serious effect comes from lepton cuts (cuts concerning the transverse momentum and pseudo-rapidity of leptons). By these cuts, the lepton energy distribution is distorted especially in the low-energy part. This causes a large shift of the zero of $I(m)$, and consequently, the correct value of the top mass is not obtained if we use the method as it is.
- We showed that the above problem of lepton cuts can be overcome by devising a method of compensating for the loss of the signal distribution caused by the lepton cuts, using MC events. For the compensated MC events, the input mass of the top quark (defined as m_t^{c}) needs to be assumed. We can extract the correct value of the top quark mass by the consistency condition that m_t^{c} is equal to the zero of $I(m)$.
- We checked that backgrounds can be suppressed appropriately by optimizing other cuts.
- As a result of a simulation study of the top mass reconstruction including the above effects with the input top mass to be 167, 170, 173, 176 and 179 GeV, we confirmed that the

correct input top mass can be obtained within the MC statistical errors.

- We studied the sensitivity of the top mass determination with this method. The signal statistical error was estimated to be 0.4GeV with an integrated luminosity of 100 fb^{-1} at the collision energy of 14 TeV. Some of major systematic uncertainties including uncertainties originating from factorization scale dependence, PDF uncertainties, jet energy scale and background statistical fluctuations were also estimated, and the uncertainty associated with factorization scale dependence was found to be the dominant one with the size of about 1.5 GeV.

The uncertainty due to factorization scale dependence, which is the dominant source of error, is expected to be improved by including higher-order corrections in this analysis, and thus, the systematic uncertainties are considered to be under control.

From these results, we demonstrated that this method is viable for the top quark mass measurement at the LHC even considering realistic experimental conditions. It has a possibility to achieve a high precision in determining a theoretically well-defined top quark mass by including higher-order QCD corrections.

論文審査の結果の要旨

川端さんは、博士論文の研究課題である LHC 実験でトップクォークの質量を高精度で決定する方法の開発で重要な成果を上げました。これは他３名との共同研究に基づきますが、全ての計算を川端さん自身が行ない、川端さんが主導している研究です。

（$\overline{\mathrm{MS}}$質量などの）理論的な意味が明確なトップ質量の精密測定は、現在の LHC 実験における最重要

課題の一つです。この方法は、川端さんら自身が提唱した weight function 法に基づき、特徴として、理想的極限でハドロン化モデル及びパートン分布関数の不定性に依らずにトップ質量を決定する方法です。原理的にそのようなオブザーバブルが存在し、カットやバックグラウンド等の影響を含めても実用に耐えることを示すことは重要です。川端さんは、実験的影響を含めたシミュレーション解析を行ない、100fb^{-1} でのトップ質量測定の統計誤差が約 0.4GeV という推定値を得ました。また主な系統誤差を十分に小さく抑えられることを示しました。この結果、この方法によるトップ質量測定の実用化に向けて大きく前進しました。

この研究開始当初、レプトン P_T カットの影響が大きいことが深刻な障害となりましたが、川端さんはこの問題を解決する方法を開発し、トップ質量の測定が現実的に可能であることを示しました。これは他の共同研究者のいずれも数か月かけても解決できなかった難問で、その解決法を独力で開発したことは、特筆すべきことです。

川端さんがこれまで学術誌に発表した（共著）論文は、最初の１本を除いて、ほぼ全てを川端さんが執筆したものです。また川端さんは、国内外の研究会における発表も精力的に行なっています。特

に、2014 年５月に CERN 研究所で開かれたトップ質量の専門家のワークショップにて、レベルの高い発表を行ないました。

2015 年 1 月 29 日に、学位論文に基づき、川端さんは 5 名の審査委員の前で堂々と自分の研究について発表を行ないました。博士学位論文の内容について 40 分の講演は明快であり、その後で出た質問に対しても適切に答えていました。

このように川端さんは自立して研究活動を行なうに必要な高度の研究能力と学識を有することを示しています。したがって、川端さやかさん提出の博士論文は、博士（理学）の学位論文として合格と認めます。